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Preventive maintenance of a single machine system working under piecewise constant operating condition

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ABSTRACT

Manufacturing machines usually work under piecewise constant operating condition (PCOC) and are subject to imperfect preventive maintenance (PM). In this paper, an extended imperfect maintenance (IM) model for a machine working under PCOC is developed by combining an age-based hybrid IM model and an accelerated failure time model (AFTM). Maximum likelihood method is provided for estimating the model parameters. A dynamic cost-effective PM policy based on a short-term production plan is proposed for a common situation where the production plan is updated dynamically and only the current operating condition (OC) is confirmed. A numerical example is conducted to demonstrate the use of the proposed policy in practice.

1. Introduction

Preventive maintenance (PM) optimization plays an increasingly important role in today's modern enterprise [1]. As more and more complex machines are being used, PM actions, such as lubrication or partial replacement, cannot rejuvenate the machines to their good-as-new states. Indeed, modeling such imperfect maintenance (IM) has attracted much attention, and many IM models have been developed [2,3], such as the (p, q) rule model [4], Brown-Proschan model [5,6], virtual age model [7–10], proportional intensity model (PIM) [11,12], ARA and ARI models [13–15], and age-based hybrid IM model [16,17]. For more complex situations, factors representing the effectiveness of maintenance have been modeled as a function of PM time interval [18–19], or a function of PM action index [16,17]. It is worth pointing out that the age-based hybrid IM model combines the age reduction and failure rate adjustment factors. Both factors depend on PM action index and indicate that the effectiveness of PM will decrease with the index. This model has been extensively adopted in the related work [16,17,31,38–41]. A drawback of this model is that the failure rate will be magnified by the adjustment factor after each action regardless of the time interval between two consecutive PM actions.

It is a common practice that machines work under different fixed or time-varying operating conditions (OC) [20–23]. In order to incorporate different OC covariates (e.g., load, speed, temperature, radiation) with an IM model, the proportional hazard rate model (PHM) [24] and accelerated failure time model (AFTM) [25] have been widely used. Remarkable work has been accomplished by the use of PHM because of its simplicity and effectiveness [26]. Some examples include combining the PHM with the age reduction [27,28], PIM [29], ARA and ARI [30], or hybrid IM [31,32] models. A drawback of PHM is that it ignores the influence of OC history on the failure rate when the covariates are time-dependent [33]. As illustrated in Fig. 1, the machine's failure rate is $h_1(t)$ if the machine is always working under OC_1 and is $h_2(t)$ under OC_2. However, in reality if the OC changes from OC_1 to OC_2 at time t_1, the PHM will consider the machine's failure rate function to be $h_2(t)$ after t_1 regardless of the OC during $0 < t < t_1$. In the literature, studies that combine the AFTM with IM is rare. One example is the combination of the AFTM with the virtual age model [34], while, it only considered the situation where OC during a PM interval is constant.

In the literature, many effective PM strategies have been developed to reduce maintenance costs [2,4,35–37]. Most of them assume that the OC covariates of production plan during the planning horizon are constant and available in advance. However, in the modern manufacture industry, inserting and changing orders occur frequently, and sequential batches are confirmed according to randomly arrived orders in a just-in-time (JIT) pattern, the information of which is released a short time beforehand [38]. The production plan is rescheduled or updated periodically or driven by certain events [39]. As a result, the corresponding PM decision needs to be optimized based on the short-term production plan as well. Recently, a few studies have been conducted on planning PM considering short-term production plans [38,40–42].

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Abbreviations

PCOC	piecewise constant operating condition
IM	imperfect maintenance
AFTM	accelerated failure time model
PM	preventive maintenance
OC	operating condition
PIM	proportional intensity model
ARI	arithmetic reduction of intensity model
ARA	arithmetic reduction of age model
PHM	proportional hazard rate model
JIT	just in time
RLPM	reliability limited preventive maintenance

Notation

$k = 1, \ldots, K$	PM action index
t_{n-1}	starting time point of the nth OC
a_k^c	classic age reduction factor
a_k	age reduction factor
p_{a1}, p_{a2}	parameters of age reduction factor
C_p	cost of an imperfect PM
C_f	cost of a minimal repair
C_r	cost of a replacement
$R_{00}(t)$	reliability in the baseline OC
$R_0(t; z_n, \ldots, z_1)$	reliability in the nth OC without PM
$R_k(t; z_n, \ldots, z_1)$	reliability in the nth OC after the kth PM
$h_{k0}(t)$	failure rate in the baseline OC after the kth PM
T_{mk}	time duration of the kth PM interval
$\boldsymbol{z_n}$	covariate vector of the nth OC
ETC	expected total cost
TR	working time of a replacement cycle
$n = 1, \ldots, N$	OC interval index
T_n	time duration of the nth OC interval
b_k^c	classic failure rate adjustment factor
b_k	failure rate adjustment factor
p_{b1}, p_{b2}	parameters of failure rate adjustment factor
T_p	time duration of an imperfect PM
T_f	time duration of a minimal repair
T_r	time duration of a replacement
$h_{00}(t)$	failure rate in the baseline OC
$h_0(t; z_n, \ldots, z_1)$	failure rate in the nth OC without PM
$h_k(t; z_n, \ldots, z_1)$	failure rate in the nth OC after the kth PM
T_{nk}	time interval of the kth PM in the nth OC
$\varphi(\boldsymbol{z_n}, \boldsymbol{\beta})$	survival time adjusting factor of the nth OC
$\boldsymbol{\beta}$	regression parameter vector
ETT	expected total time
CR_c	cost rate of a replacement cycle

The contribution of this study is two-fold. First, an extended IM model for machines working under piecewise constant operating condition (PCOC) is developed by combining the AFTM and age-based hybrid IM model. The extended IM model takes into account the influence of OC history and integrates the time-varying OC with the IM model. In particular, the residual age and failure rate adjustment caused by each imperfect PM action are modeled as functions of PM time interval and action index. This provides a more reasonable way for modeling the reliability behavior of complex machines. To estimate the model parameters, maximum likelihood method is also provided. Moreover, a dynamic cost-effective PM policy based on a short-term production plan is developed, which shows better performance than several popular alternatives [38, 40–42].

The remainder of this paper is organized as follows: Section 2 provides an elaborate introduction to the extended IM model and a recursive algorithm for parameter estimation. Section 3 presents a PM policy based on a short-term production plan. Section 4 provides a numerical example to investigate the properties of the proposed models and PM policy. Finally, Section 5 concludes the paper.

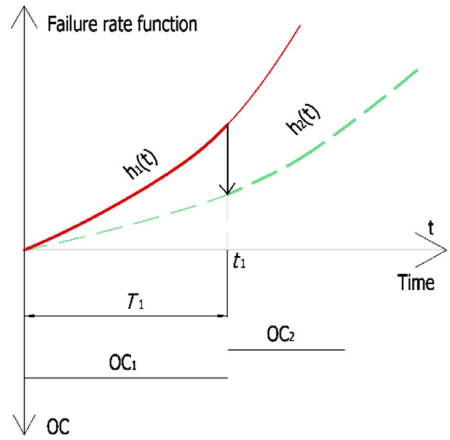

Fig. 1. Evolution of hazard rate function with OC shift for PHM.

2. Models and parameter estimation

In this section, the abbreviation, notation, and assumption will be presented first. Then, the evolution models of reliability and failure rate when OC changes will be addressed. The extended IM model for a machine working under PCOC will be developed based on the evolution models. Finally, a parameter estimation method will be provided.

The following assumptions are made for developing the proposed models and PM policy.

1. The failure time distribution of the machine working under different OC can be modeled by an AFTM. The parametric form and parameter values of survival time adjusting factor are fixed.
2. The machine is new when it starts to work. IM is implemented at each PM time. Minimal repair is carried out when a failure happens during a PM interval without altering the machine's failure rate. The machine will be replaced after several imperfect PM actions, and the machine's state will be renewed.
3. The time will be reset to 0 after each PM action.

2.1. Evolution models of reliability and failure rate function

A new machine starts to work at time $t_0 = 0$, and it will go through a sequence of N OC as illustrated in Fig. 2. The OC covariate vector and time duration of N OC are $(\{\boldsymbol{z}_1, T_1\}, \ldots, \{\boldsymbol{z}_n, T_n\}, \ldots, \{\boldsymbol{z}_N, T_N\})$. The survival time adjusting factor of the nth OC is $\varphi(\boldsymbol{z_n}, \boldsymbol{\beta})$, which represents the joint effect of covariate vector $\boldsymbol{z_n}$. One example is the operation of a CNC machine, where the feed rate, cutting depth and rotational speed change under different batches according to a CNC program.

Based on the AFTM, the reliability function of the machine during the 1st OC interval, $t_0 \le t < t_1$, can be expressed as

$$R_0(t; \boldsymbol{z}_1) = \exp\left[-\int_0^{\varphi(\boldsymbol{z}_1, \boldsymbol{\beta})t} h_{00}(s)ds\right] = R_{00}[\varphi(\boldsymbol{z}_1, \boldsymbol{\beta})t] \tag{1}$$

where $h_{00}(t)$ and $R_{00}(t)$ are the baseline failure rate and reliability function of the machine without PM operations, respectively. With Eq. (1), the failure rate function during the 1st OC can be expressed as

$$h_0(t; \boldsymbol{z}_1) = -[dR_0(t; \boldsymbol{z}_1)/dt]/R_0(t; \boldsymbol{z}_1) = \varphi(\boldsymbol{z}_1, \boldsymbol{\beta})h_{00}[\varphi(\boldsymbol{z}_1, \boldsymbol{\beta})t] \tag{2}$$

In practice, the OC may change at time t_1. Such a case is often encountered when the production of one batch is completed and the process is shifted to another batch. In fact, it is quite common that the OC covariate vector varies from one batch to another. Then, the reliability function during the 2nd OC interval, $t_1 \le t < t_2$,